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# Structural Geology in the Kiewa Region of the Metamorphic Complex, North-East Victoria

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Abstract: The detailed study of structure in three small areas is described. One area, the Tawonga Gap, is in low grade rocks on the western margin of the Complex; the second, the Snowy Creek area, Mitta Mitta, is similarly in low grade rocks on the eastern margin; the third area is Mt. Beauty, in the main high grade belt of High Plains Gneiss. It is established that (i) folds of at least two generations (and locally three) occur in the lower grade rocks on the margin: both groups of folds are Benambran; (ii) two generations of folds occur in the High Plains Gneiss, but these are not necessarily equivalent to the folding in the lower grade rocks; (iii) in the Tawonga Gap area, the boundary between slates and phyllites and the higher grade schists is in part transitional, in part faulted. The faulting is more complex than along the West Kiewa margin of the Complex.

A tentative relationship between folding, metamorphism, faulting and igneous activity in the Kiewa region is proposed.

## INTRODUCTION

Igneous and metamorphic petrology, jointing and faulting in the Kiewa Region have been described previously (Beavis 1960, 1962). Folding in the metamorphic rocks was not examined more than superficially in the earlier work, and since 1962, therefore, field work has been directed to this aspect of the structure. It soon became apparent that the earlier (1962) analysis of folding was an over-simplification. Because detailed structural mapping of the whole region was almost impossible, three small areas were selected (See Fig. 1). Two of these are on the west (Tawonga Gap) and east (Snowy Creek) margins of the main high grade metamorphic belt and the third was chosen within the High Plains Gneiss, at Mt. Beauty where, in addition to excellent exposures, we were able to map the complete length of a tunnel across the area.

The region generally is notable for the extremely poor exposures, and the three areas were selected for exposures, particularly in road cuttings, which were better than elsewhere in the region. Two notes have been published previously (Beavis 1963, 1968); the earlier recorded two generations of folds at Snowy Creek, the later established, in the Tawonga Gap area, the nature of the foliation and in particular of the lithological layering, in the schists.

This paper describes structures in the three areas, and the regional generalizations drawn from the results. In addition, the nature of the metamorphic boundary in the Tawonga Gap area is described. Finally, using data presented here, and that presented in earlier publications, an attempt is made to relate faulting, igneous activity, folding and metamorphism in the region.

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## METAMORPHIC ZONES IN THE KIEWA REGION

Seven metamorphic zones may be recognized in the regions:—

(i) *Zone of Slates:* Traditionally, the rocks of this zone have been regarded as non-metamorphic, and the margin of the metamorphic complex has been placed where the pelitic rocks show the development of a strong recrystallization schistosity. The rocks of the zone consist of sandstones, siltstones and slates; the two latter are strongly foliated (cleaved) and lineated, and all have undergone some recrystallization. The slates are pale grey, aluminous types with rare beds, particularly in the Mitta Mitta Valley, of black, highly

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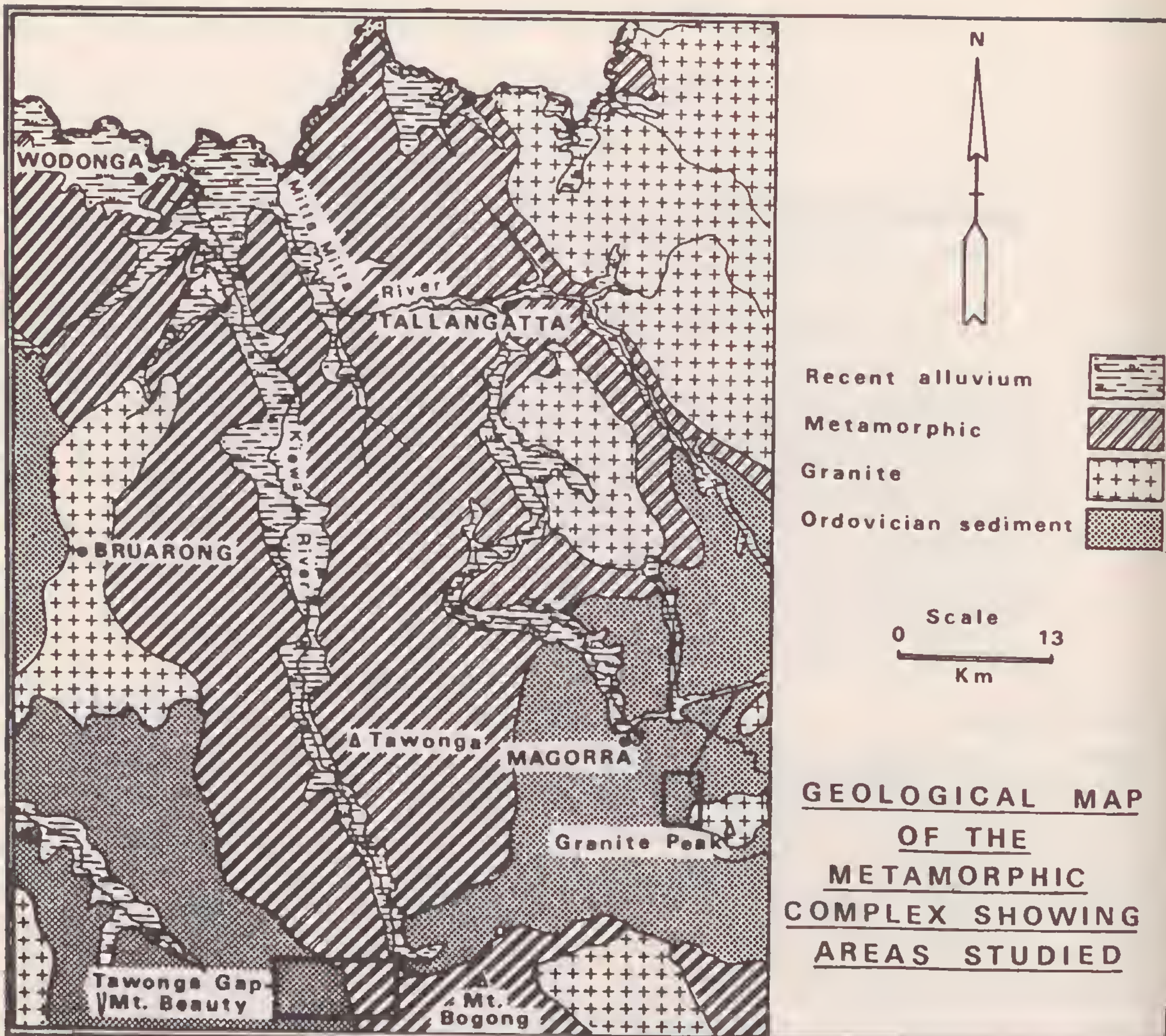


FIG. 1—Map of the North-East Metamorphic Complex showing the areas studied.

carbonaceous slate. The sandstones are quartzitic, or more commonly greywacke types. The latter are graded and normally pass upwards into laminated siltstones.

(ii) *Zone of Phyllites:* The pelitic rocks of this zone are fine satin textured, silver-grey-green in colour. High in the zone, the siltstones become phyllitic and bedding laminations show advanced transposition into the plane of the cleavage. The sandstones differ from those of the lower zone only in a more advanced recrystallization of the micas.

(iii) *Zone of Chlorite Quartz Albite Schists:* Because of the combined effects of transposition and metamorphic segregation, the pelites and semi-pelites have a strong lithological layering, with laminae of quartz and albite alternating with thicker chlorite-rich laminae. Within this zone, transposition of bedding laminae in the finer sediments into the plane of the foliation is complete. The sandstones show more advanced recrystallization, with albite the dominant feldspar. Primary sedimentary structures are difficult to discern, and, with the exception of graded bedding, are lost. Gross bedding separation surfaces can be distinguished.

(iv) *Zone of Biotite Schist:* Strongly foliated and lineated biotite schist alternates with bands of quartz schist and quartz feldspar schist. It is considered that these represent, respectively, the original pelitic and psammitic beds. The quartz feldspar schists are poorly foliated, but lineation

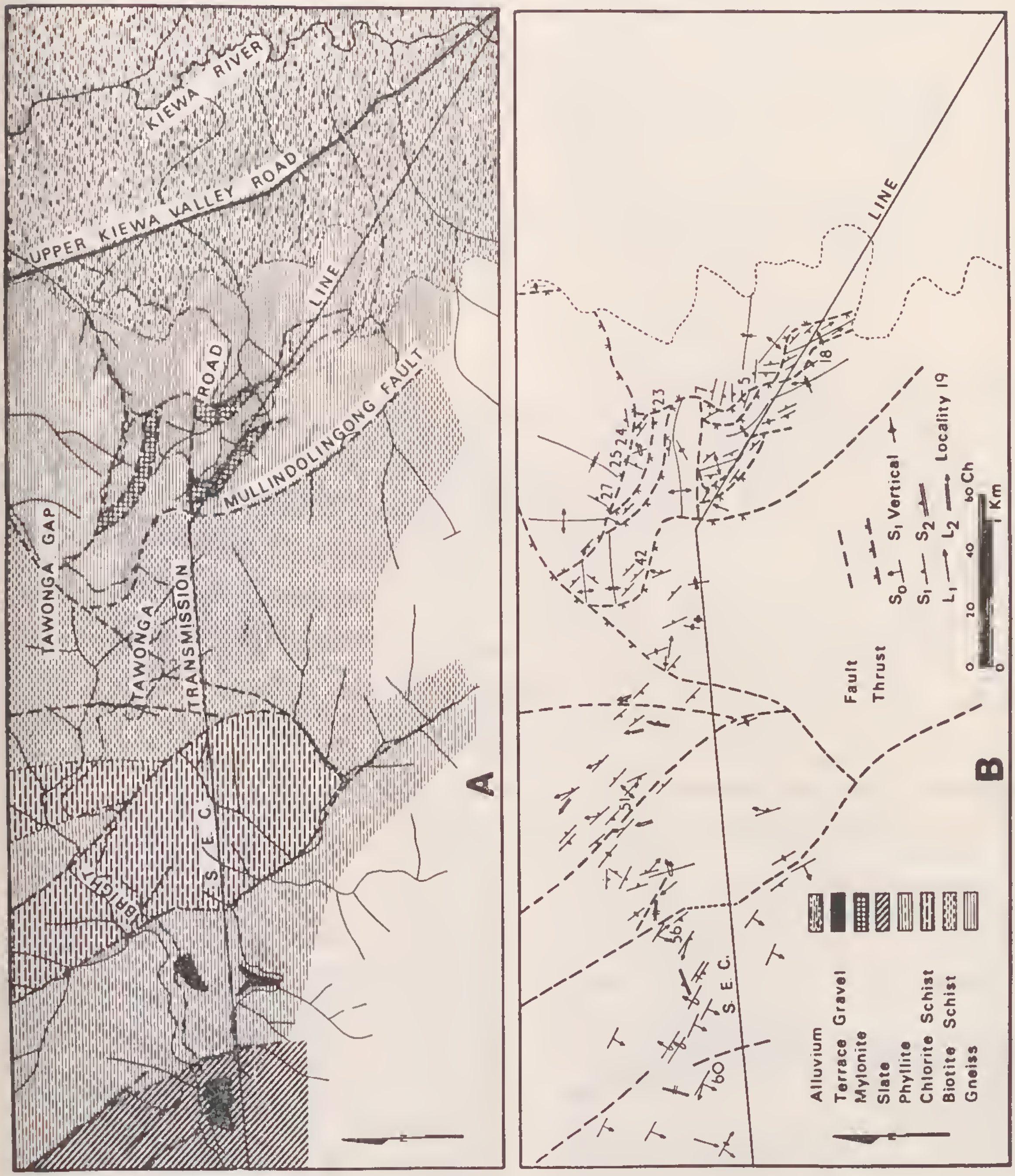


FIG. 2—Geological map of the Tawonga Gap area.

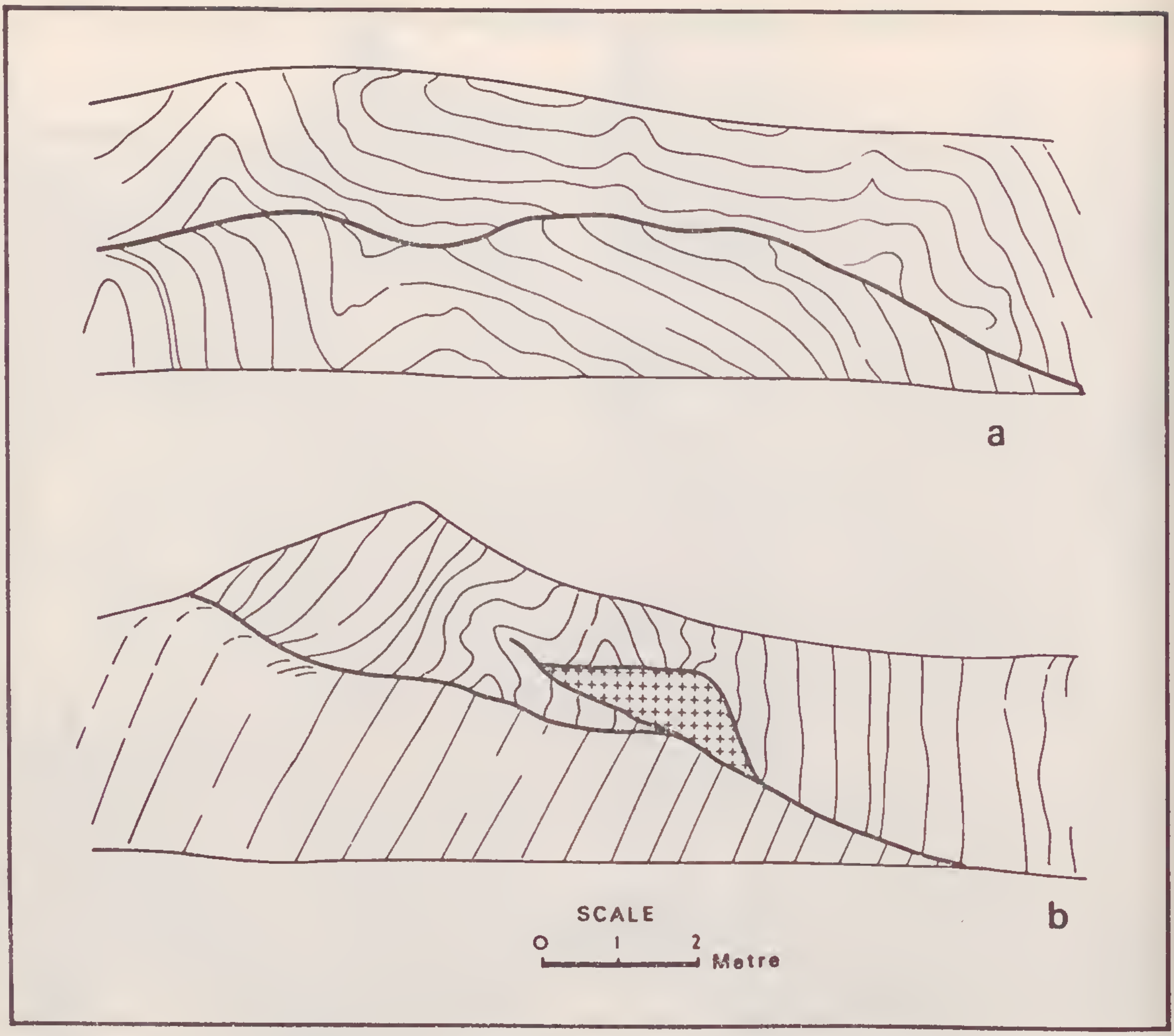


FIG. 3—Drawings of low angle thrusts in the High Plains Gneiss, Tawonga Gap.

tends to be more prominent than in the biotite schists.

(v) *Zone of Cordierite Schist:* Field distinction of original rocks is not possible, usually, in this zone, although some bands of quartz amphibole schist may represent original sandstones. Although foliation is prominent, lineation tends to be weak, the most noteworthy lineation being due to the dimensional orientation of the pinitized cordierite porphyroblast knots.

Biotite, cordierite and quartz are essential constituents but locally, particularly high in the zone, sillimanite, almandine and muscovite became important.

(vi) *Zone of Sillimanite Almandine Schist:* The schists of this zone are strongly foliated and coarse textured with some localized development of a coarse discontinuous lithological layering. The essential minerals are quartz; oligoclase; black, almost opaque biotite, partially replaced by sillimanite; almandine.

(vii) *High Plains Gneiss:* It has been emphasized (Beavis 1962, Leggo & Beavis 1968, Leggo 1968) that the 'typical' High Plains Gneiss does not exist. It is a strongly banded rock, but schistosity may be extremely prominent, weak, or absent. Segregation of biotite, and of quartz and feldspar into nodules is characteristic; this was considered by Tattam (1929) and Beavis (1962) to be due to the addition of igneous material, but Leggo (1968) has shown quite conclusively that this is not the case and that the nodules are a product of metamorphic segregation.

## THE TAWONGA GAP AREA

Tawonga Gap is a low saddle, 666·3 m above sea level, on the north-south divide separating the Kiewa and Ovens Valleys. The area is one of deep weathering and thick vegetation, with few natural exposures. The data shown on Fig. 2 were derived for the most part from fresh cuttings on the Bright-Mt. Beauty road which passes through the Gap.

South from the Gap, the High Plains Gneiss is bounded on the north-west by the Tawonga Fault (Beavis 1960) and on the west by the West Kiewa Thrust Zone (Beavis 1962). Between Tawonga and Mt. Beauty township, some gneiss is exposed but this gives way very rapidly to chlorite quartz albite schist in Symonds Creek. The relationship between the two is unknown.

*The Metamorphic Boundary at Tawonga Gap*

Although in one section a transition from slate to phyllite was observed, all of the boundaries of the metamorphic zones which occur in this area (Slate, Phyllite, Chlorite-quartz-albite schist, Biotite schist) are faulted (Fig. 2). It was not possible, therefore, to determine either the width of the zones or the width of each zone removed by faulting. By comparison with the Mt. Blowhard-Mt. Hotham section to the south, it is clear that a considerable thickness of the Zone of Phyllites has been faulted out at Tawonga Gap, and by comparison with the eastern margin, it would seem that considerable thicknesses of the Biotite Schist and Biotite Sillimanite Almandine Schist Zones have been removed by faulting, and all of the Zone of Cordierite Schist.

Further south, in the valley of the West Kiewa River, the boundary between the High Plains Gneiss and the Zone of Phyllites is relatively simple and is marked by the West Kiewa Thrust Zone. At Tawonga Gap, the boundary faulting is a complex of high and low angle thrusts, although one, the Mullindolingong Fault, is more significant than the others since it forms the boundary between the Zone of Biotite Schist and the High Plains Gneiss. It must be stressed, however, that even the lesser faults are important since they were responsible for the faulting out of the lower grade rocks.

Low angle thrusts cutting the High Plains Gneiss are shown on Fig. 3 and Pl. 7. These structures generally dip at less than 10° and they may be horizontal. Most are irregular with both dips and strikes varying widely. The thickness of crush zones varies: that of brecciated zones is 0·2 to 1·0 m, and of mylonitized zones between 1 and 100 m. The breccia is slabby, with the platy surfaces lying parallel to the walls of the crush zone. The mylonites are fresh and form the boldest outcrop in the area; they are strongly foliated, with folding of the foliation common.

Near the thrusts, the gneissic foliation has been deformed by drag, and associated with drag is a system of radial joints. Apart from this jointing, the wall rocks are extensively broken by other joint systems, the intensity of jointing increasing closer to the thrusts, but the boundary of the crush zone is always sharp and clearly defined. The low angle structures appear to be restricted to the gneiss, on the Kiewa fall of the Divide. In the lower grade rocks of the Ovens fall, the faults are almost invariably high angle thrusts with dips of 70°. Strike is northerly. In all cases, the crush zones are brecciated and the crush zone is always less than 10 m thick.

Exposures of the Mullindolingong Fault are poor; the best is at locality 42 (Fig. 2) where it strikes SE. and dips 30° NE. Because one wall is obscured by alluvium and slip debris the thickness of the crush zone is uncertain. It consists of brecciated gneiss and biotite schist, with lenses of mylonite. Immediately north of Tawonga Gap the fault appears to dip more steeply and to strike NE. Near the Tawonga Gold Mine, strike is N. with dip 20° E. South of the Tawonga Gap only one exposure was found, in a small gully; here the fault appears to be horizontal.

The age of the faulting is unknown, but in view of the two sets of attitudes and the two types of crush zone material, two periods of faulting would seem to have been effective.

*Folding in the Tawonga Gap Area*

Folds of two generations have been recognized in both the low grade metamorphic rocks and in the High Plains Gneiss. The folds have been designated $F_1$ and $F_2$ where $F_1$ are the older. The $F_1$ folds of the gneiss are not necessarily equivalent to the $F_1$ folds of the low grade rocks. There is, in fact, some evidence to be presented later in this paper, that $F_1$ folds in the gneiss are the equivalent of $F_2$ folds in the low grade rocks.

*The High Plains Gneiss*

Lithological layering $S_1$ in the gneiss, frequently weak and discontinuous, is an emphasis of the lithological layering of the schists. The structure is in part original bedding and in part bedding transposed into the axial plane of the $F_1$ folds of the low grade rocks. In the gneiss, there is a schistosity $S_1$ parallel to the lithological layering. Folds in $S_1$ of the gneiss have a faint axial plane foliation $S_2$, which is defined by trains of biotite. Lineations and linear structures are rarely prominent, although one good example is shown on

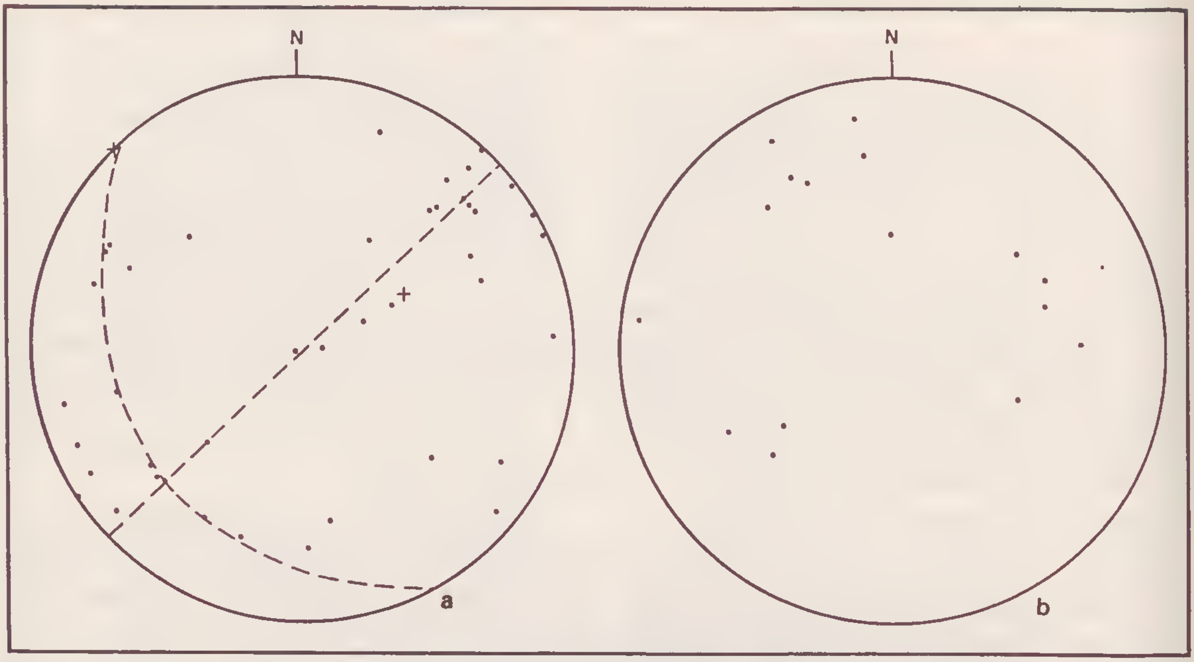


FIG. 4—Equal area projection of structural elements of the High Plains Gneiss, Tawonga Gap: a. Poles to foliation in gneiss; b. Lineations in gneiss.

Pl. 7, fig. 4, and another on Pl. 8, fig. 2. The former example, crenulations on biotite layers, is $L_1$ deformed in a $F_2$ synform.

The styles of the two generations of folds are quite distinct, and each generation (and style) has a more or less well defined trend. $F_1$ folds are open, with rounded hinge zones, planar to slightly curved limbs, and a weak axial plane foliation $S_2$. The $F_1$ folds may be symmetrical, isoclinal, and they may be upright or recumbent, but asymmetrical upright folds are more typical. Fold axes trend between N30°E. and N30°W. The trend of $F_2$ folds is E.-W. These folds have a rounded to box like profile, and occur as isolated flexures in an otherwise uniformly dipping $S_1$.

On Fig. 4 are shown equal area projections of the structural elements. Data were inadequate for analysis. Field observations showed that $F_1$ folds, with northerly trend, plunged from 5° to 45°. $F_2$ folds have plunges to east or west, and while it may vary from less than 10° to over 70°, steep plunge is the more common. Fig. 4a shows a tentative interpretation of poles to $S_1$ lying in two girdles with poles $B_1$ and $B_2$. The lineations recorded are clustered about these poles, but with less than 20 lineations recorded, it is not possible to generalize.

*The Low Grade Metamorphics*

In the slates and phyllites, bedding $S_0$ is the most prominent structural element, but in the schists, foliation $S_1$ (schistosity and lithological layering, which are parallel) dominates the structure. Except in $F_1$ fold hinges, $S_0$ and $S_1$ are parallel or nearly so, which is indicative of isoclinal folding. This type of folding was directly observed at a number of localities. Lineation $L_1$ is a set of coarse microfolds with wave length 2-5 mm, the larger being observed in the higher grade schists (Pl. 8, figs. 3 and 4). Locally, cleavage mullions occur in the slates (Pl. 8, fig. 1).

All of the $F_1$ structures have been deformed by the later $F_2$ movement, and in the low grade rocks $F_2$ folds, the associated axial plane cleavage $S_2$, and lineations $L_2$, are all important structural elements. All of the $F_2$ folds appear to be small mesoscopic structures, and no large $F_2$ folds were observed. Without exception, plunge of $F_2$ folds is steep.

The effects of the deformation of $F_1$ structures by $F_2$ movements are shown on Pl. 6, fig. 3, and on Fig. 5. The deformation of $L_1$ is of particular interest. On the assumption that $L_1$ was here originally horizontal, the development of the present pattern can be seen to have occurred by slip on $S_2$. The surface $S_1$ which contains $L_1$ also contains $L_2$ due to the intersection of $S_1$ and $S_2$.

The near coincidence of $\pi S_0$ and $\pi S_1$ on Fig. 6 indicates not only the essential parallelism of

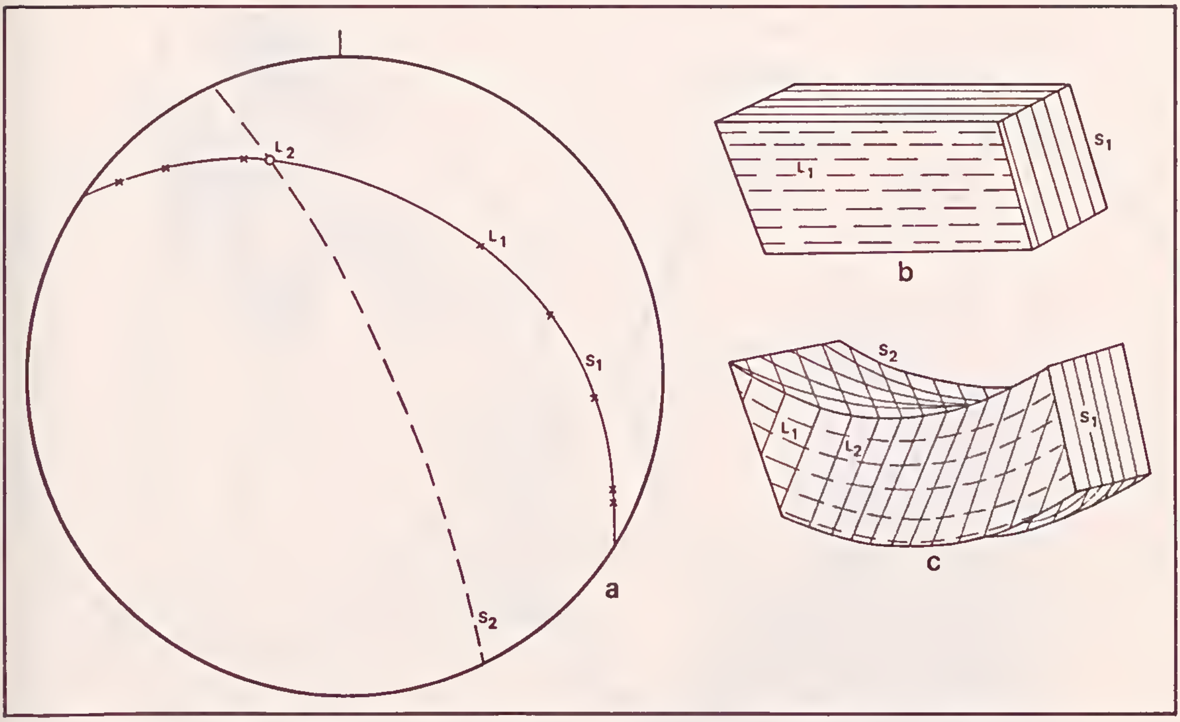


FIG. 5—a. Equal area projection showing deformed $L_1$ at locality 43; b., c. Diagrams showing progress of deformation.

these two elements, but also their common folding about the axis of the $F_2$ folds. $L_1$ tends to lie in a girdle which contains $\beta S_0$ $S_1$, while there tends to be a concentration of $L_2$ at $\beta_2$. The synoptic diagram shows the possible relationship of the elements.

## THE SNOWY CREEK AREA

The importance of this area is in the fact that evidence is available permitting the dating of the $F_1$ and $F_2$ folds in the low grade rocks. The area lies on the eastern margin of the metamorphic complex, and the rocks examined all lie within the Zone of Phyllites. Kenny (1937) first noted structural complexity, which was shown later (Beavis 1963) to be due to several generations of folds having been developed in the rocks. At the southern extremity of the area, the slates, phyllites and sandstones are faulted against relatively high grade schists, and have been intruded by the Banimboola Granodiorite, which has imposed a contact metamorphism on the slates and sandstones (Fig. 7).

### *Structural Elements and Their Relationships*

Bedding, $S_0$ is the most prominent element of the structure, tending to obscure other planar elements. In many cases, examination of sawn faces was necessary to determine the nature of the form surface of a fold, the prominence of $S_0$ obscuring the fact that $S_1$ was an element which had been folded also. Slaty cleavage $S_1$ is strongly developed in the pelitic rocks and, where contact metamorphism has been effective, this structure has received an emphasis so that it becomes a fine schistosity. Except in the hinge zones of $F_1$ folds, $S_1$ and $S_0$ are either parallel or intersect in an extremely acute angle.

Cleavages and kink bands $S_2$ may be more pronounced in some of the pelitic rocks than $S_1$. $S_2$ forms the axial surface of $F_2$ folds; $S_2$ normally cuts $S_0$ and $S_1$ at high angles, although sometimes $S_1 \lambda S_2$ is very sharp, and occasionally the two are parallel. The absence of $S_2$ from the sandstones suggests that the deformation of the pelitic rocks by slip on $S_2$ was the major $F_2$ activity. $F_3$ elements ($S_3$) are of two types, but both are fracture cleavages. One is a set of fractures parallel to the axial planes of $F_3$ folds, the other is a set of *en echelon* fractures forming kink bands. Whereas both $F_1$ and $F_2$ structures have been emphasized by contact metamorphism, $F_3$ structures have not, and clearly post-date the Banimboola intrusive activity.

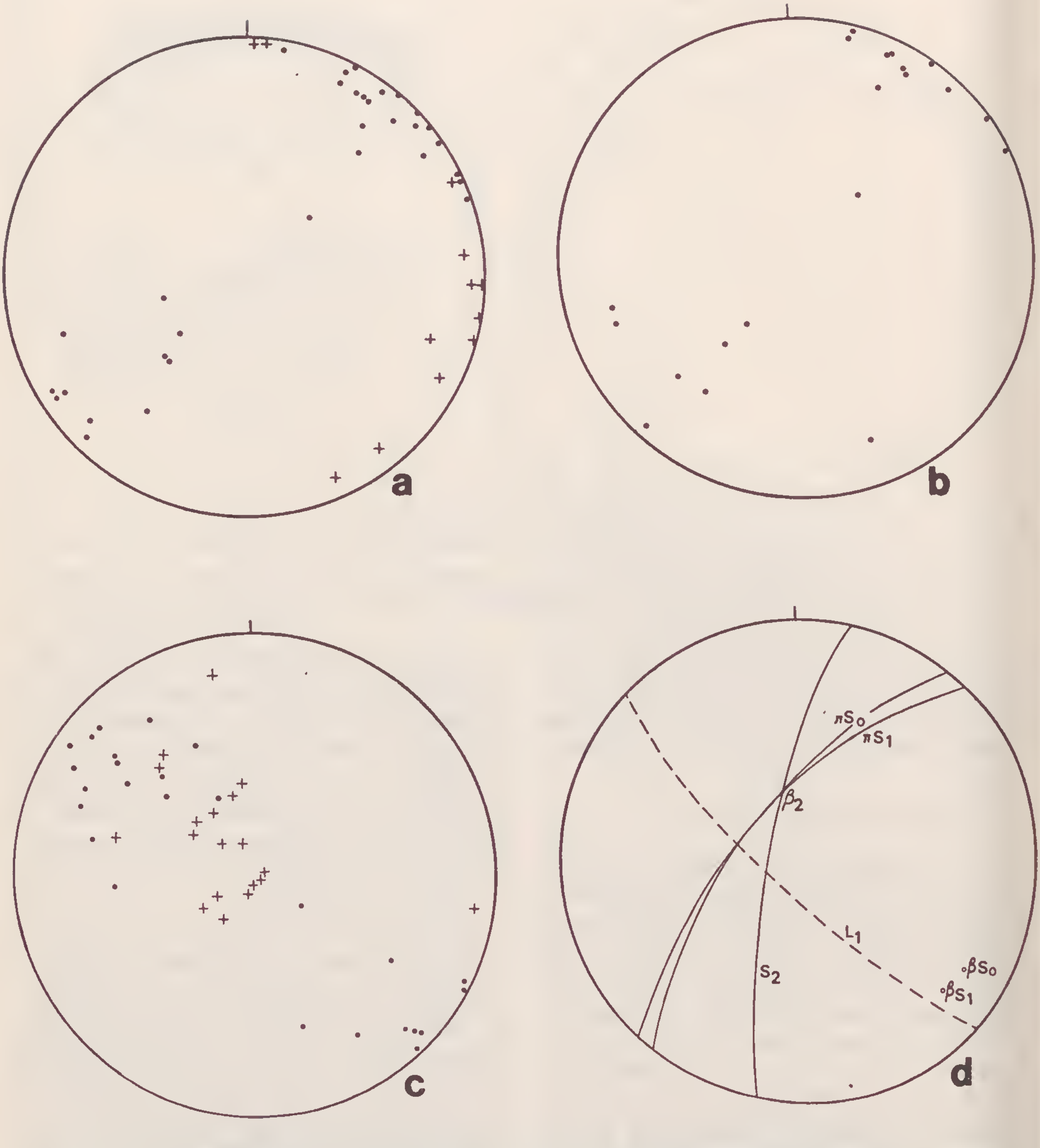


FIG. 6—a. Equal area projection of poles to $S_2$ (0) and $S_1$ (+); b. Equal area projection of poles to $S_2$; c. Equal area projection of $L_1$ (0) and $L_2$ (+); d. Synoptic diagram: Tawonga Gap.

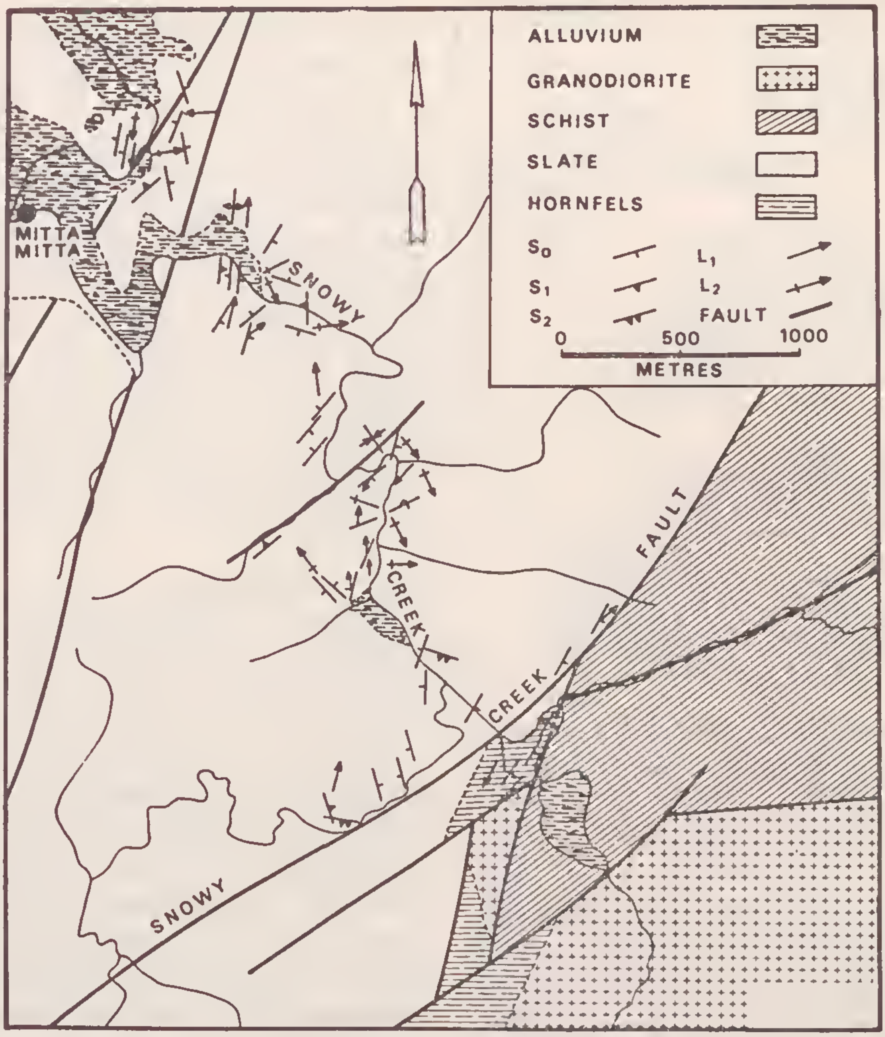


FIG. 7—Geological map of Snowy Creek area.

Three generations of linear structure occur. Lineations $L_1$ are due to $S_0$-$S_1$ intersection in the slates and phyllites: in the siltstones it is formed by the hinges of small folds; fold mullions are prominent linear elements in the sandstone. Cleavage mullions are extremely common $L_2$ structures, but $L_2$ may also be an intersection structure.

$F_1$ folds have a 'similar' style. Large folds with axial plane separation of 10 m are typical. The folds tend to be symmetrical, isoclinal, upright, but asymmetrical and even recumbent $F_1$ folds were observed. $F_2$ fold style is controlled by the lithology. In laminated siltstones, the folds have rounded hinges with axial plane separation of 3 cm to over 3 m. $S_0$ is apparently the form surface, but close study shows that $S_1$ is folded. In slates and phyllites, the folding tends to be cuspate, with the production of mullions: the synforms are open and rounded, the antiforms are sharply cuspate. These folds contain a penetrative crenulation cleavage, $S_2$, and a discrete fracture cleavage, $S_2$, which is restricted to the axial surface of the antiforms. Parallel style folds are restricted to coarser sandstones (Pl. 7, fig. 2). Since these rocks are poorly cleaved, the recognition of the folds as $F_2$ structures is difficult unless they contain deformed $F_1$ elements. The rare $F_3$ folds have a chevron style associated with which are the broad kink bands. These folds were noted only near Granite Flat.

The complexity of the fold geometry at the mesoscopic scale can be seen on Fig. 8, where two examples, one from the Mitta Mitta Gorge (a,b) and one from Snowy Creek 1·8 km up-

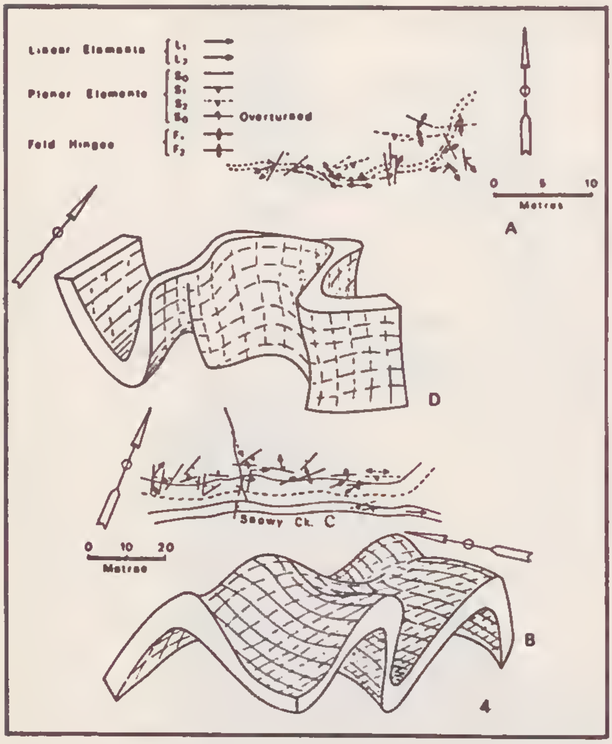


FIG. 8—Folding in the Snowy Creek area: a. Map of elements at Mitta Mitta Gorge, Mitta Mitta; b. Reconstruction of folding from data in a.; c. Map of elements, Snowy Creek; d. Reconstruction of folding from data of c.

stream from Mitta Mitta township, are illustrated. Both $F_1$ and $F_2$ folds have a wide variety of plunges, but generally, $F_1$ folds have a gentle plunge and $F_2$ folds plunge sharply. 'Overturned' plunging of some $F_1$ folds was noted. The projection of structural elements is shown on Fig. 9. The more or less similar distribution of $S_0$ and $S_1$ demonstrates the folding of both of these surfaces about the same axes during the $F_2$ movements. The poles to $S_0$ and $S_1$ lie in a more or less horizontal girdle with pole $\beta_2$ vertical. There is some suggestion of an E.-W. vertical girdle, with pole $\beta^1$ horizontal trending a few degrees E. of N.: the pattern of $\pi S_0$ alone does not demonstrate two phases of folding. $F_1$ folding was probably about gently plunging N.-S. areas, while $F_2$ was about one with trend NNW.-SSW. with steep plunge. The axial surfaces of $F_2$ folds have steep dips with strike WNW.

*Age of the Folding*

Throughout the area, $F_2$ structures have been superimposed on $F_1$ structures, with $F_3$ structures restricted to narrow belts near major faults. Recrystallization accompanied $F_1$ folding, but there is no evidence of either progressive or retrogressive metamorphism associated with the $F_2$ movements.

The low grade metamorphic rocks have been intruded by the Banimboola Granodiorite which has imposed a contact metamorphism and given a mimetic emphasis to $F_1$ and $F_2$ cleavages and lineations. The folding therefore predates intrusion. The Banimboola Granodiorite is overlain by the Mitta Mitta Volcanics, which in turn are overlain by the middle to upper Silurian Wombat Creek Group (Singleton 1965). The Granodiorite, therefore, is clearly early Silurian or epi-Ordovician, probably Benambran in age. Both $F_1$ and $F_2$ folds must therefore also be Benambran, and each must represent a distinct phase of the Benambran movement. The $F_3$ structures post date intrusion; the age of these folds is unknown.

## THE MT. BEAUTY AREA

Folding in the High Plains Gneiss is considered in this section of the paper. The fundamental problem has been the determination of the nature of the foliation in the gneiss. Here, this is considered from the structural point of view. Leggo (1968) has considered the same problem from a petrological-geochemical basis.

The basic assumption made in this paper is that the High Plains Gneiss was derived from the sandstones and slates which flank the complex. This was considered to be the case by Tattam (1929) after petrological studies, Beavis (1962) from structural studies and Leggo (1968) after geochemical research. Since, on the western margin of the Complex, the boundary is faulted, evidence there is unavailable to support the basic assumption. On the eastern margin although faulting occurs, there does *appear* to be a transition from slate to gneiss. It is doubtful, however, if work of sufficient detail has yet been carried out to establish this transition with certainty.

Earlier in this paper it was shown that, in the Zone of Slates, three surfaces are present: $S_0$, $S_1$ and $S_2$. On the limbs of $F_1$ folds $S_0$ and $S_1$ are essentially parallel, but they intersect at a high angle in the hinge zones. Due to the initiation of transposition of $S_0$ into the plane of $S_1$ there tends, even here, to be a parallelism between the two structures. In the Zone of Phyllites transposition is more advanced, although major separation bedding planes show no evidence of transposition. Within the Zone of Chlorite Quartz Albite Schists there is a fine schistosity in the chlorite layers, and a strong layering due to complete transposition of $S_0$ into the plane of

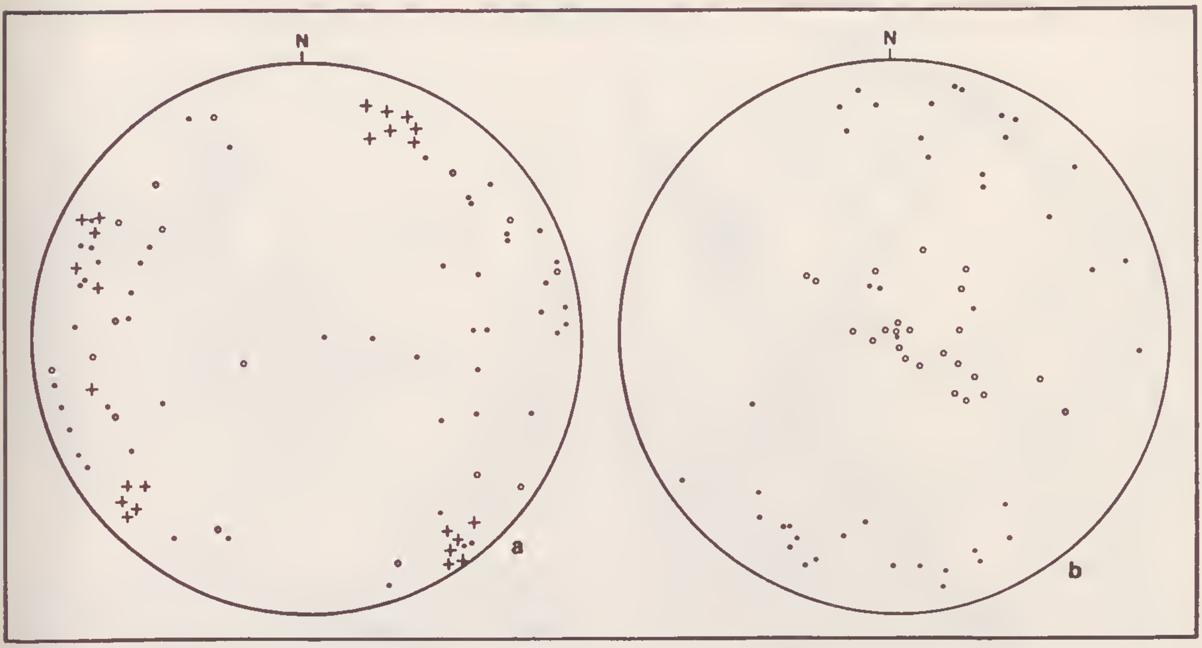


FIG. 9—a. Poles to $S_0$ (0), $S_1$ (0) and $S_2$ (+) in the Snowy Creek area; b. Projection of $L_1$ (0) and $L_2$ (0) in the Snowy Creek area.

$S_1$ and the marked progress of metamorphic segregation: the schistosity and layering are parallel, and major $F_1$ fold hinges can still be recognized. In the Zone of Biotite Schists lithological layering and schistosity $S_1$ dominate the structure. Major bedding separation planes can be seen only where layers of quartz schist occur interbedded with biotite schist.

The strongest planar structure in the Zone of Cordierite Schists is schistosity, due to the preferred dimensional orientation of quartz and biotite. Lithological layering is weak or absent, but bedding planes separating quartz amphibole schist and cordierite biotite schist can be readily distinguished. With transition to the Zone of Biotite Sillimanite Almandine Schists, lithological layering parallel to the schistosity again becomes prominent. The layering becomes at first progressively more pronounced, then discontinuous, and with the development of quartz-feldspar and biotite nodules, the schist passes into the High Plains Gneiss. Within the gneiss itself both the schistosity and layering are irregular, and in places, belts of non-foliated rock occur. These are poor in biotite and sillimanite, and may represent original thick beds of sandstone.

The schistosity of the micaceous layers is parallel to the layering even on fold hinges. However, some folds contain a weak schistosity parallel to the axial planes, which cuts the banding in the hinge zone, at a high angle. From this evidence it is clear that the banding and dominant schistosity $S_1$ have been derived from cleavage (and bedding transposed along the cleavage) in the low grade rocks. The weak axial plane schistosity present in some folds in the gneiss is $S_2$ developed during the $F_1$ folding and deformed during the $F_2$ folding, so that it is not seen in $F_2$ folds in the gneiss. The implication is that since $F_1$ structures of the low grade rocks are folded in $F_1$ folds in the gneiss, the latter are of later stage than the former and that the $F_1$, $F_2$, . . . folds of the low grade rocks are not equivalent to the $F_1$, $F_2$, . . . folds in the gneiss.

*Macroscopic Fold Patterns in the High Plains Gneiss*

On Fig. 10 have been recorded the attitudes and trends of the foliations $S_1$ in the gneiss in the Mt. Beauty area. Macroscopic fold hinges observed, and interpreted from the data are shown. It must be stressed that the interpretation of the folding was made in the absence of any lithological marker.

Several features are noteworthy:

(i) The frequency of horizontal or near horizontal foliations $S_1$;

(ii) The existence of two quite definite fold trends, one of which may be deformed by the other;

(iii) The development of overturned and recumbent folds.

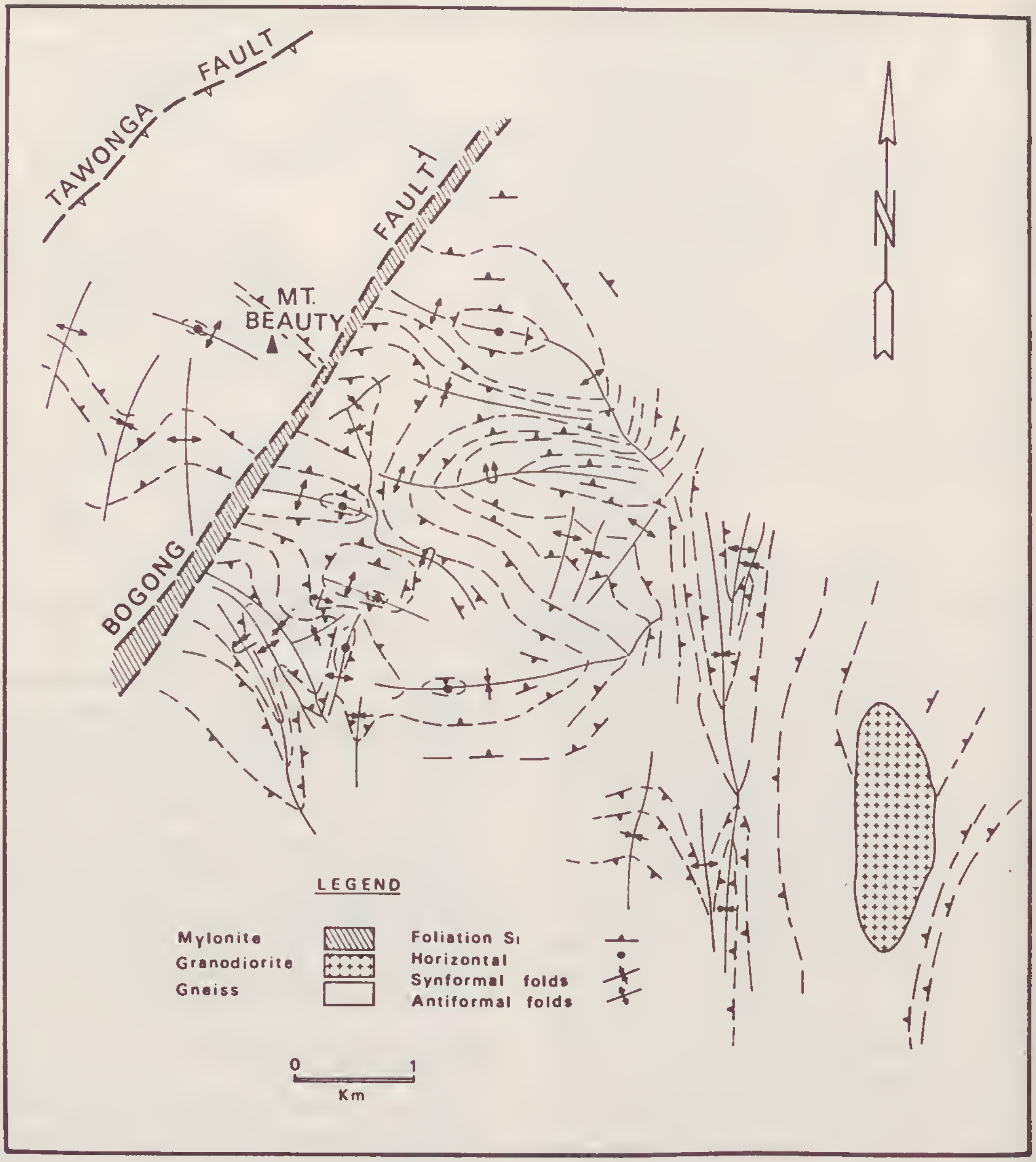


Fig. 10—Macroscopic folding in the High Plains Gneiss, Mt. Beauty.

The horizontal foliation appears to occur in two situations:

(i) on the limbs of recumbent folds, and

(ii) in areas of interference between the two sets of folds.

The projection of poles to $S_1$ for this area (Fig. 11) reflects the complexity of the folding, and suggests that Fig. 10 may be an over-simplification. The most prominent girdle, with pole $\beta_I$, corresponds to one set of fold hinges. $\beta_{II}$ corresponds approximately to the second set of fold hinges, but there are other possible girdles which seem unrelated to folding. It is unfortunate that outcrop data are inadequate for the isolation of attitudes which contribute to the several girdles. So far as field observation is concerned, there is evidence of only two sets of folds.


FIG. 11—Poles to foliation in gneiss at Mt. Beauty. Equal area projection, 224 poles. Contours 1, 2, 3, 5, 10, 15%.

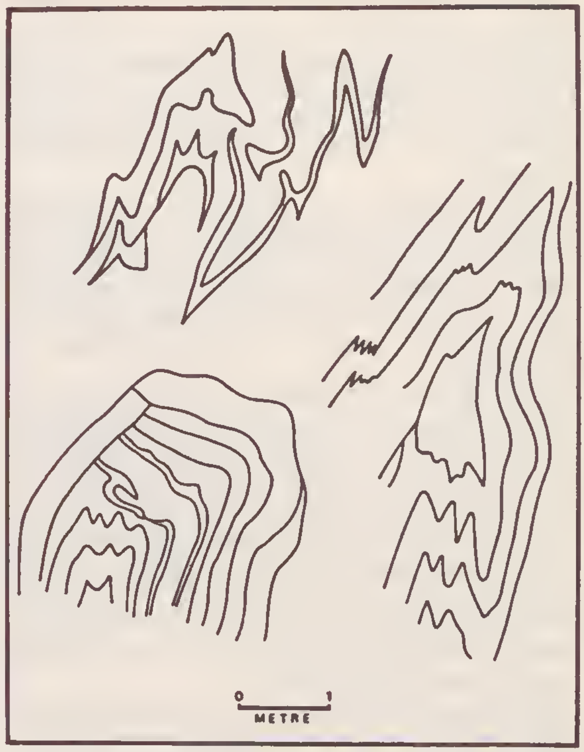


FIG. 12—Mesoscopic folds in High Plains Gneiss.

*Mesoscopic Folds in the High Plains Gneiss*

Two sets of mesoscopic folds were noted in the High Plains Gneiss at Tawonga Gap (p. 65). Some typical folds in the gneiss in the Mt. Beauty area are shown in Fig. 12. All of the $F_1$ folds have a 'similar' style, with generally sharp angular hinges, but rounded hinges may occur. In some cases, hinges have been isolated and these may be evidence (Fig. 12) of an earlier (= $F_1$ of low grade rocks) folding. $F_2$ folds tend to be isoclinal with rounded hinges and are generally smaller than $F_1$ folds. Axial plane foliation is absent.

The study of the mesoscopic folds confirms that the $F_1$ folds in the gneiss have, as form surface, structures imposed during $F_1$ deformation of the lower grade rocks. It is believed that:
(i) $F_2$ folds in gneiss have no equivalent in the low grade rocks;
(ii) $F_1$ folds in gneiss $\equiv$ $F_2$ folds of low grade rocks;
(iii) $F_1$ folds of low grade rocks are represented in the gneiss only as isolated fold hinges, and otherwise have been destroyed.

## METAMORPHISM, FOLDING, FAULTING AND IGNEOUS ACTIVITY IN THE KIEWA REGION

It is apparent that the metamorphic and tectonic history of the Metamorphic Complex is much less simple than indicated by previous workers (Tattam 1929, Crohn 1949, Beavis 1962). Table 1 shows a summary of the history of folding, metamorphism, faulting and igneous activity. This table is a presentation of relationships discussed in the remainder of this paper.

*Folding*

Three phases of folding have occurred:
(a) $F_1$ folds in low grade metamorphics ($P_1$).
(b) $F_2$ folds in low grade metamorphics and $F_1$ folds in high grade schists and High Plains Gneiss ($P_2$).
(c) $F_2$ folds in high grade metamorphics and High Plains Gneiss ($P_3$).

In addition there is evidence of minor localized phases of folding, e.g. $F_3$ folds in low grade rocks at Snowy Creek, Beechworth and Mt. Feathertop, and $F_3$ kink bands in High Plains Gneiss, mesoscopically, at Mt. McKay, and possibly macroscopically, although the evidence of this latter is not convincing. It is not justifiable to recognize a fourth phase of general folding in the Kiewa Region.

The first phase of folding, $P_1$, can now be recognized only in the low grade to medium grade metamorphic rocks. Folding was about gently plunging N.-S. axes; the folds are frequently isoclinal, and $S_1$, developed during this phase, is parallel, for the most part, to bedding. Recumbent folds occur rarely. Folding of this phase in the low to medium grade rocks are designated $F_1$. Only rarely is there any evidence of folds of this phase in the high grade schists and gneiss.

The second phase of folding, $P_2$, of $S_1$ about steeply to gently plunging axes trending E.-W. to NW.-SE., is represented by $F_2$ folds in the low grade rocks, and $F_1$ folds in the high grade rocks. A crenulation foliation $S_2$ was developed. The folds are sometimes isoclinal, but may be recumbent.

Folds of the third phase, $P_3$, of general folding are restricted to the high grade metamorphics and constitute the $F_2$ folds in these rocks. The two surfaces $S_1$ and $S_2$ have been folded, and no axial plane foliation appears to have been formed.

$F_3$ folds in sediments, low grade and high grade metamorphics are very localized, and are of varying age: e.g. $F_3$ folds occur near the Snowy Creek Fault, in the aureole of the Beechworth Batholith, and near major faults of Mt. Feathertop and Mt. McKay.

The age of the folding is uncertain, but it is clear that in the Snowy Creek area $F_1$ and $F_2$ folds in the low grade rocks are Benambran, i.e. fold phases $P_1$ and $P_2$ are Benambran, and there is no evidence to suggest that $P_3$, the third phase, is not Benambran. This being the case, the Benambran folding must be considered as having had at least two, and possibly three, distinct phases with a differently oriented stress system for each phase.

Folds of the first phase are found only in low grade rocks. Transposition and metamorphic segregation have effectively destroyed these folds in the high grade metamorphics, and $F_1$ folds in the high grade rocks are to be regarded as second phase structures, which are present also in the lower grades as $F_2$ structures. The absence of a regional third phase of folding, $P_3$, in the lower grade schists, phyllites and slates, though folds of this phase are prominent in the High Plains Gneiss, requires some consideration.

The region occupied by high grade schists and the High Plains Gneiss obviously represent the deeper zones of the orogenic belt, and, as pointed out by Whitten (1966, p. 501), it is highly unlikely that each phase of folding at depth is necessarily reflected in rocks at shallow depth in a totally different tectonic environment. It should not be necessary to demand that all phases of folding were effective at all tectonic levels in an orogenic belt. If such a demand has to be met, it would be necessary, in the present case, to challenge relationships between the low grade schists and the High Plains Gneiss which, while admittedly not established beyond all possibility of dispute, rest on criteria assembled from a number of different approaches. That is, if it is demanded that phase $P_3$ folds be developed in all of the metamorphic rocks, the derivation of the high grade rocks from the slates must be rejected.

*Metamorphism*

The more important aspects of the metamorphic rocks are:

(i) the onset of metamorphic differentiation in very low grade slates;

(ii) the persistence of lithological layering throughout the metamorphic sequence, with a temporary weakening in the Zone of Cordierite Schists;

(iii) the weakening of schistosity from near the top of the cordierite zone;

(iv) the bending of the schistosity by growing cordierite porphyroblasts;

(v) pinitization of cordierite and sillimanite;

(vi) the existence of two generations of biotite in the high grade schists and gneiss, one of which is fibrolitized and dark coloured, the other light, strongly pleochroic, and which has not been fibrolitized;

(vii) large lenses of biotite; and of quartz and microcline, in the High Plains Gneiss.

Of lesser importance to the regional picture is the development of porphyroblasts of dark mauve cordierite and bright red andalusite in the biotite sillimanite almandine schist and in gneiss. These occur only in contact zones about later granodiorites. Textural and petrological evidence (Tattam 1929, Crohn 1949, Beavis 1962) indicate that the Complex is polymetamorphic, with the last main phase, $M_3$, one of the retrograde activity. Phase $M_4$ was localized about later intrusions. The first phase of metamorphism ($M_1$) is regarded as being more or less synchronous with the first phase of folding ($P_1$). The sediments were converted to slates, phyllites and low grade biotite schists. A fine schistosity was induced, and transposition of bedding occurred. At a later stage of $M_1$, metamorphic segregation began with the migration of quartz into the hinge zones of small folds and into kink bands. This emphasized the lithological layering due to transposition.

The second phase of metamorphism, $M_2$, was marked by the development of cordierite porphyroblasts, garnet and sillimanite, with the fibrolitization of earlier formed biotites and the development of second generation biotite. In the deeper parts of the orogenic belt, metamorphic segregation tended to emphasize the layering but with a

Table 1

FOLDING, METAMORPHISM, FAULTING AND IGNEOUS ACTIVITY IN THE KIEWA REGION

| FOLDING (P) | | METAMORPHISM (M) | | IGNEOUS ACTIVITY (I) | | FAULTING (C) | | OROGENY |
|---|---|---|---|---|---|---|---|---|
| Phase | Event | Phase | Event | Phase | Event | Phase | Event | |
| $P_1$ | Initial folding of sediments about N-S axes. Isoclinal folds in $S_o$. | $M_1$ | Syntectonic development of schistosity and layering. Growth of biotite. | | | | | Benambran |
| $P_2$ | $F_2$ folding of sediments and schists about steeply plunging axes. $F_1$ folding of High Plains Gneiss. | $M_2$ | Syntectonic growth of cordierite, garnet, sillimanite. Emphasis of layering. | | | | | |
| $P_3$ | $F_2$ folding of High Plains Gneiss. Localised $F_3$ folding of low grade rocks and gneiss. | $M_3$ | Syntectonic retrograde pinitization of cordierite. | $I_{1a}$ | Intrusion of Granodiorite:- post-tectonic. | $C_1$ | High angle thrusting - West Kiewa Thrust. | |
| | | | | $I_{1b}$ | Extrusion of Mitta Mitta Volcanoes. | | | |
| | | | | $I_2$ | Syntectonic intrusion of Pretty Valley Granodiorite. | | | Bowning |
| | | $M_4$ | Contact metamorphism of High Plains Gneiss $\rightarrow$ andalusite and cordierite. | $I_3$ | Post-tectonic intrusion of East Kiewa and Niggerheads Granodiorite. | | | Tabberabberan |
| | | | | $I_4$ | Post-tectonic intrusion of Big Hill Quartz Diorite. | $C_2$ | Wrench faulting - Nelse, Spion Kopje. Early wrench movement of Tawonga Fault. | |
| | | | | $I_5$ | Pre to syntectonic extrusion of Bogong Volcanics. | $C_3$ | Low angle thrusting on Tawonga, Snowy Creek and Mullindolingong Faults. | Kosciuskoan |